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**Friction and Wear Properties of Selected Solid Lubricating Films
Part 1: Bonded and Magnetron-Sputtered Molybdenum Disulfide and Ion-Plated Silver
Films**

Friction and Wear Properties of Selected Solid Lubricating Films

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Summary

To evaluate commercially developed solid film lubricants for aerospace bearing applications, an investigation was conducted to examine the friction and wear behavior of bonded molybdenum disulfide (MoS_2), magnetron-sputtered MoS_2 , and ion-plated silver films in sliding contact with 6-mm-diameter American Iron and Steel Institute (AISI) 440C stainless steel balls. Unidirectional sliding friction experiments were conducted with a load of 5.9 N (600 g), a mean Hertzian contact pressure of 0.79 GPa (maximum Hertzian contact pressure, 1.19 GPa), and a sliding velocity of 0.2 m/s. The experiments were conducted at room temperature in three environments: ultrahigh vacuum (vacuum pressure, 7×10^{-7} Pa), humid air (relative humidity, ~20 percent), and dry nitrogen (relative humidity, <1 percent). The resultant films were characterized by scanning electron microscopy, energy-dispersive x-ray spectroscopy, and surface profilometry.

Marked differences in the friction and wear of the bonded MoS_2 , magnetron-sputtered MoS_2 , and ion-plated silver films investigated herein resulted from the environmental conditions and the solid lubricating film materials. The main criteria for judging the performance of the solid lubricating films were coefficient of friction and wear rate, which had to be less than 0.3 and on the order of 10^{-6} $\text{mm}^3/\text{N}\cdot\text{m}$ or less, respectively. The bonded MoS_2 and magnetron-sputtered MoS_2 films met the criteria in all three environments. Also, the wear rates of the counterpart AISI 440C stainless steel balls met that criterion in all three environments. The ion-plated silver films met the criteria only in ultrahigh vacuum but failed in humid air and in dry nitrogen. In humid air and dry nitrogen both the silver film wear rate and the ball wear rate were higher than the criteria and on the order of 10^{-5} $\text{mm}^3/\text{N}\cdot\text{m}$.

In ultrahigh vacuum the coefficient of friction and endurance (wear) life of the bonded MoS_2 films were superior to those of the magnetron-sputtered MoS_2 and ion-plated silver films. In humid air, an oxidative environment, the bonded MoS_2 films had higher coefficient of friction (0.14) and shorter wear life (113 570 passes) than those (0.10 and 277 377 passes, respectively) of the magnetron-sputtered MoS_2 films. The ion-plated silver films had a high coefficient of friction (0.43) in humid air but relatively low coefficients of friction in the nonoxidative environments (0.20 in ultrahigh vacuum and 0.23 in dry nitrogen).

Adhesion and plastic deformation played important roles in the friction and wear of the solid lubricating films in sliding contact with 440C stainless steel balls in the three environments. All sliding involved adhesive transfer of materials: transfer of solid lubricant wear debris to the counterpart 440C stainless steel and transfer of 440C stainless steel wear debris to the counterpart solid lubricant.

Introduction

Tribology, the multidisciplinary science of lubrication, friction, and wear, is application oriented, with a rich methodology. Once the initial shortcomings relating to lubrication in design and application had been dealt with, it became increasingly clear that materials science and technology ranked equal with design in reducing the friction and wear of machinery and mechanical components (ref. 1). This conclusion applied particularly in the field of aerospace mechanisms.

In modern technology coefficient of friction and wear are regarded to be widely variable, depending on operational variables, lubricants, substrate properties, and surface films. Therefore, testing is central, and particularly round-robin testing at different laboratories is of great importance to tribologists, lubrication specialists, designers, and engineers.

This present investigation was conducted at NASA Glenn Research Center to examine the friction and wear properties of three types of solid lubricating film in ultrahigh vacuum, in humid air at a relative humidity of ~20 percent, and in dry nitrogen at a relative humidity of less than 1 percent. The three types of solid lubricating film selected were bonded molybdenum disulfide (MoS_2), magnetron-sputtered MoS_2 , and ion-plated silver, which were furnished by the National Space Development Agency of Japan (NASDA) through K Systems Corporation (Dayton, Ohio) under a Space Act Agreement. Unidirectional pin-on-disk sliding friction experiments were conducted with 440C stainless steel balls in sliding contact with the solid lubricating films at room temperature in ultrahigh vacuum, in humid air, and in dry nitrogen. The resultant solid lubricating films and their wear surfaces were characterized by scanning electron microscopy (SEM), energy-dispersive x-ray spectroscopy (EDX), and surface profilometry. SEM and EDX were used to determine the morphology and elemental composition of wear surfaces and wear debris. The sampling depth of EDX for elemental information ranged between 0.5 to 1 μm in this investigation. Surface profilometry was used to determine the surface morphology, roughness, and wear of the films.

Selected Materials

Three specimens of each type of film (bonded MoS_2 , magnetron-sputtered MoS_2 , and ion-plated silver) produced on 440C stainless steel disk substrates were used in this investigation (table I). The bonded MoS_2 films were relatively rough, having a centerline-average roughness R_a , measured using a cutoff of 1 mm, of 1.2 μm with a standard deviation of 0.24 μm . The magnetron-sputtered MoS_2 films were relatively smooth, having an R_a , measured using a cutoff of 1 mm, of 32 nm with a standard deviation of 4.0 nm. The ion-plated silver films were also relatively smooth, having an R_a , measured using a cutoff of 1 mm, of 30 nm with a standard deviation of 3.2 nm. The 6-mm-diameter 440C stainless steel balls (grade number, 10) used were also smooth, having R_a of 0.025 μm with a standard deviation of 0.02 μm or less.

Experiment

The pin-on-disk tribometer used in the investigation was mounted in a vacuum chamber (fig. 1). Unidirectional pin-on-disk sliding friction experiments were conducted at room temperature in ultrahigh vacuum (7×10^{-7} Pa), in humid air (relative humidity, ~20 percent), and in dry nitrogen (relative humidity, <1 percent). All experiments were conducted with 6-mm-diameter 440C stainless steel balls in sliding contact with the solid lubricating films deposited on 440C stainless steel substrate disks. All experiments were conducted with a load of 5.9 N (600 g) at the sliding velocity of 0.2 m/s. The mean Hertzian contact pressure of the 440C stainless steel substrates in contact with the 440C stainless steel balls was ~0.79 GPa (maximum Hertzian contact pressure, 1.19 GPa). The pin-on-disk tribometer can measure friction in vacuum, in humid air, and in dry nitrogen during sliding. The friction force was continuously monitored during the friction experiments.

The sliding wear life for the coatings (film wear life, or film endurance life) in this investigation was determined to be the number of passes at which the coefficient of friction rose to 0.3 in a given environment. Wear can be quantified by measuring the wear scars and wear tracks on the specimens after the wear experiments. Film wear volumes were obtained by measuring the average cross-sectional area, determined from stylus tracings, across the wear tracks at a minimum of eight locations in each wear track. Then, the average cross-sectional area of the wear track was multiplied by the wear track length. The wear rate, known as the dimensional wear coefficient, is defined as the volume of material removed at a unit load and in a unit sliding distance expressed as cubic millimeters per newton-meter.

Results and Discussion

Friction Behavior

Figures 2 to 4 present typical friction traces obtained in ultrahigh vacuum, in humid air, and in dry nitrogen for the bonded MoS_2 , magnetron-sputtered MoS_2 , and ion-plated silver films in sliding contact with 440C stainless steel balls as a function of the number of passes.

Ultra-high-vacuum environment.—The friction traces for the bonded MoS₂ and magnetron-sputtered MoS₂ films obtained in vacuum are smooth, but the friction trace for the ion-plated silver films fluctuates (fig. 2). The coefficient of friction for the bonded MoS₂ films gradually increased to ~0.05 at 1 million passes. The coefficient of friction for the magnetron-sputtered MoS₂ films suddenly rose from 0.06 to 0.3 at 274 130 passes. The coefficient of friction for the ion-plated silver films gradually increased to 0.3 at 364 793 passes from 0.2 at the initial stage of the experiment.

Figure 2 reveals that in ultrahigh vacuum the coefficient of friction and endurance life of the bonded MoS₂ films were superior to those of the magnetron-sputtered MoS₂ and ion-plated silver films.

Humid-air environment.—The coefficient of friction for the bonded MoS₂ films began relatively high and gradually increased to ~0.16 at ~80 000 passes (fig. 3). It then became erratic and rose to 0.3. The coefficient of friction for the magnetron-sputtered MoS₂ films was relatively high and fluctuating. The coefficient of friction for the ion-plated silver films rapidly rose to 0.3 in a small number of passes, say 10 passes.

Figure 3 reveals that in humid air the coefficient of friction and endurance life of the bonded MoS₂ and magnetron-sputtered MoS₂ films were superior to those of the ion-plated silver films. Furthermore, the tribological performance of the three types of solid lubricating film was much better in ultrahigh vacuum than in humid air.

Dry-nitrogen environment.—The friction traces for the bonded MoS₂ and magnetron-sputtered MoS₂ films obtained to 1 million passes in dry nitrogen are smooth, but the friction trace for the silver films obtained to 1040 passes fluctuates (fig. 4). The coefficient of friction for ion-plated silver gradually increased to 0.3 at 1040 passes.

Figure 4 reveals that in dry nitrogen the coefficient of friction and endurance life of the bonded MoS₂ and magnetron-sputtered MoS₂ films were superior to those of the ion-plated silver films.

Wear Behavior

Figures 5 to 7 present SEM photomicrographs of wear scars on the 440C stainless steel balls and wear tracks on the solid lubricating films deposited on 440C stainless steel disks after sliding contact in ultrahigh vacuum, in humid air, and in dry nitrogen, respectively. The SEM observations were made either at the end of the wear life of the solid lubricating films or at 1 million passes.

The wear scars on the 440C stainless steel balls were generally smooth, regardless of either the type of solid lubricating film or the environment. Thin, smeared wear patches and particles of the solid lubricating films generally covered the smooth wear scars. Smeared tongues of thin, layered, agglomerated wear debris were also present. Most of the loose and smeared wear debris accumulated outside the wear scars.

The wear tracks on the solid lubricating films revealed that the sliding action usually generated a smooth wear surface, fine wear debris particles, and agglomerated, pasty wear debris, regardless of the environment. The wear tracks on the ion-plated silver films in ultrahigh vacuum and in dry nitrogen revealed delaminated, flat plate-like wear debris.

Wear Life (Endurance Life)

The sliding wear (endurance) life for the solid lubricating films deposited on 440C stainless steel disks was determined to be the number of passes at which the coefficient of friction rose to 0.3. The sliding wear lives are presented in figure 8 and table II.

The sliding wear life varied with the environment and the type of solid lubricating film. The wear lives of the bonded MoS₂ films were over 1 million passes in ultrahigh vacuum and in dry nitrogen but only 113 570 passes in humid air. The wear lives of the magnetron-sputtered MoS₂ films in dry nitrogen were over 1 million passes, much greater than in ultrahigh vacuum and in humid air. The wear lives of the ion-plated silver films were relatively greater in ultrahigh vacuum than in dry nitrogen and in humid air.

In ultrahigh vacuum the bonded MoS₂ films had longer wear lives than the magnetron-sputtered MoS₂ and ion-plated silver films. In humid air the wear lives of all three solid lubricating films were relatively short. In dry nitrogen the bonded MoS₂ and magnetron-sputtered MoS₂ films had longer wear lives than the ion-plated silver films.

Comparison of Steady-State Coefficients of Friction and Wear Rates

Table II and figure 9 present the steady-state coefficients of friction, the wear rates for the solid lubricating films, and the wear rates for the 440C stainless steel balls after sliding contact in all three environments. The data presented in the table reveal the marked differences in friction and wear resulting from the environmental conditions and the solid lubricating film materials.

Both the bonded MoS₂ and magnetron-sputtered MoS₂ films had low coefficients of friction and low wear rates in ultrahigh vacuum and in dry nitrogen but relatively high coefficients of friction and high wear rates in humid air. Also, the 440C stainless steel balls that slid against the bonded MoS₂ and magnetron-sputtered MoS₂ films had low wear rates in ultrahigh vacuum and in dry nitrogen but moderate wear rates in humid air.

In contrast to the bonded MoS₂ and magnetron-sputtered MoS₂ films, the ion-plated silver films had a higher coefficient of friction and greater wear rates in all three environments. However, the lowest values for the silver films were obtained in the ultra-high-vacuum environment.

Ultra-high-vacuum environment.—In sliding contact with 440C stainless steel balls in ultrahigh vacuum the bonded MoS₂ films had the lowest coefficient of friction, lowest film wear rate, and lowest ball wear rate. The magnetron-sputtered MoS₂ films also had low coefficient of friction, low film wear rate, and low ball wear rate. The ion-plated silver films had relatively low film and ball wear rates but a high coefficient of friction.

Humid-air environment.—In sliding contact with 440C stainless steel balls in humid air the magnetron-sputtered MoS₂ films had the lowest coefficient of friction. Both bonded MoS₂ and sputtered MoS₂ films generally had low coefficients of friction, low film wear rates, and low ball wear rates in humid air. However, the ion-plated silver films had high friction and high wear.

Dry-nitrogen environment.—In sliding contact with 440C stainless steel balls in dry nitrogen the magnetron-sputtered MoS₂ films had the lowest coefficient of friction. Both the bonded MoS₂ and sputtered MoS₂ films had low coefficients of friction, low film wear rates, and low ball wear rates. However, the ion-plated silver films had high friction and high wear.

Sliding Wear, Wear Debris, and Transferred Wear Fragments

Adhesion and plastic deformation played important roles in the friction and sliding wear of the solid lubricating films in sliding contact with the 440C stainless steel balls in all three environments. The worn surfaces of both the films and the balls contained wear debris particles. Examining the morphology and composition of the worn surfaces by SEM and EDX provided detailed information about plastic deformation of the solid lubricating films, wear debris, and transferred wear fragments produced during sliding (figs. 10 to 20). Marked plastic deformation occurred in the three solid lubricating films. Smeared, agglomerated wear debris accumulated around the contact border, particularly on the ends of wear scars. All sliding involved adhesive transfer of materials.

Ultra-high-vacuum environment.—Figure 10(a) presents a typical wear track on a bonded MoS₂ film over which a 440C stainless steel ball has passed in ultrahigh vacuum leaving transferred steel wear fragments. The asperities (or texture) of the bonded MoS₂ were deformed plastically and the tips of the asperities were flattened under a load during sliding. The wear scar on the counterpart 440C stainless steel ball (fig. 10(b)) contained transferred wear fragments of MoS₂. Wear fragments of MoS₂ and 440C stainless steel usually adhered to the other surface or came off in loose form. Another form of adhesive transfer of MoS₂ is found in sliding wear. SEM and EDX showed that a thin MoS₂ layer (or sheet) was generated over the entire wear scar of a 440C stainless steel ball.

Figure 11(a) presents a typical wear track on a magnetron-sputtered MoS₂ film over which a 440C stainless steel ball has passed in ultrahigh vacuum leaving transferred steel wear fragments. The fine asperities of the sputtered MoS₂ film were flattened and elongated in the direction of sliding by plastic deformation, revealing a burnished appearance. The wear scar on the counterpart 440C stainless steel ball (fig. 11(b)) contained transferred wear fragments of MoS₂. However, according to the elemental concentrations, much less transfer occurred between the 440C stainless steel balls and the films and vice versa with the magnetron-sputtered MoS₂ (figs. 11(a) and (b)) than with the bonded MoS₂. With the magnetron-sputtered MoS₂ a thin MoS₂ layer was also generated over the entire wear scar of the 440C stainless steel ball.

Figure 12(a) presents a typical wear track on an ion-plated silver film over which a 440C stainless steel ball has passed in ultrahigh vacuum leaving a small amount of transferred steel wear fragments. The fine asperities of the ion-plated silver film were flattened and elongated in the direction of sliding by plastic deformation, revealing a

burnished appearance. The entire wear scar on the counterpart 440C stainless steel ball (fig. 12(b)) contained thick transferred layers (or sheets) of silver. Plate-like silver debris particles were found at the edges of the wear track on the ion-plated silver film, as shown, for example, in figure 13. Severe plastic deformation and shearing occurred in the silver film during sliding.

Humid-air environment.—Figure 14(a) presents a typical wear track on a bonded MoS₂ film over which a 440C stainless steel ball has passed in humid air leaving a small amount of transferred steel wear fragments. The asperities of the bonded MoS₂ were deformed plastically and the tips of the asperities were flattened under a load during sliding. The wear scar on the counterpart 440C stainless steel ball (fig. 14(b)) contained a large amount of transferred MoS₂ wear fragments. Wear debris particles usually adhered to the other surface or came off in loose form. Also, a thin MoS₂ layer (or sheet) was generated over the entire wear scar on the 440C stainless steel ball.

Figure 15(a) presents a typical wear track on a magnetron-sputtered MoS₂ film over which a 440C stainless steel ball has passed in humid air leaving transferred steel wear fragments. The fine asperities of the sputtered MoS₂ film were flattened and elongated in the direction of sliding by plastic deformation, revealing a burnished appearance. The wear scar on the counterpart 440C stainless steel ball (fig. 15(b)) contained transferred MoS₂ wear fragments. The elemental concentrations of 440C stainless steel transferred to the films in humid air were greater with the sputtered MoS₂ film than with the bonded MoS₂ film. On the other hand, the elemental concentrations of MoS₂ transferred to the 440C stainless steel were much less with the sputtered MoS₂ than with the bonded MoS₂. A thin MoS₂ layer was also generated over the entire wear scar on the 440C stainless steel ball.

Figure 16(a) presents a typical wear track on an ion-plated silver film over which a 440C stainless steel ball has passed in humid air leaving a small amount of transferred steel wear fragments. The fine asperities of the ion-plated silver film were flattened and elongated in the direction of sliding by plastic deformation, revealing a burnished appearance. Significantly, the wear scar on the counterpart 440C stainless steel ball (fig. 16(b)) contained an extremely small amount of transferred silver debris particles. This result suggests that oxidation of silver during sliding in humid air may prevent large silver transfer. In addition to the small wear debris particles, plate-like silver debris was found at the edges of the wear track on the ion-plated silver film, as shown, for example, in figure 17. Severe plastic deformation and shearing occurred in the silver film during sliding.

Dry-nitrogen environment.—Figure 18(a) presents a typical wear track on a bonded MoS₂ film over which a 440C stainless steel ball has passed in dry nitrogen leaving a small amount of transferred steel wear fragments. The asperities of the bonded MoS₂ were deformed plastically, and the tips of the asperities were flattened under a load during sliding. The wear scar on the counterpart 440C stainless steel ball (fig. 18(b)) contained a large amount of transferred MoS₂ wear fragments. The wear debris particles usually adhered to the other surface or came off in loose form. Also, a thin MoS₂ layer (or sheet) was generated over the entire wear scar on the 440C stainless steel ball.

Figure 19(a) presents a typical wear track on a magnetron-sputtered MoS₂ film over which a 440C stainless steel ball has passed in dry nitrogen leaving transferred steel wear fragments. The fine asperities of the sputtered MoS₂ film were flattened and elongated in the direction of sliding by plastic deformation, revealing a burnished wear track. The wear scar on the counterpart 440C stainless steel ball (fig. 19(b)) contained transferred MoS₂ wear fragments. The elemental concentrations of 440C stainless steel transferred to the films in dry nitrogen were greater with the sputtered MoS₂ film than with the bonded MoS₂ film. On the other hand, the elemental concentrations of MoS₂ transferred to the 440C stainless steel were much less with the sputtered MoS₂ than with the bonded MoS₂. A thin MoS₂ layer was also generated over the entire wear scar on the 440C stainless steel ball.

Figure 20(a) presents a typical wear track on an ion-plated silver film over which a 440C stainless steel ball has passed in dry nitrogen leaving a small amount of transferred steel wear fragments. The fine asperities of the ion-plated silver film were flattened and elongated in the direction of sliding by plastic deformation, revealing a burnished appearance. The wear scar on the counterpart 440C stainless steel ball (fig. 20(b)) contained transferred silver debris and particles. In addition to the small wear debris particles, plate-like silver debris was found at the edges of the wear track on the ion-plated silver film. Severe plastic deformation and shearing occurred in the silver film during sliding.

Conclusions

To evaluate commercially developed solid film lubricants for aerospace bearing applications, unidirectional sliding friction experiments were conducted with bonded molybdenum disulfide (MoS₂), magnetron-sputtered MoS₂, and ion-plated silver films in contact with AISI 440C stainless steel balls in ultrahigh vacuum, in humid air,

and in dry nitrogen. The main criteria for judging the performance of the solid lubricating films were coefficient of friction and wear rate, which had to be less than 0.3 and on the order of 10^{-6} mm³/N·m or less, respectively. The following conclusions were drawn:

1. The bonded MoS₂ and magnetron-sputtered MoS₂ films met the criteria in all three environments.
2. The wear rates of the counterpart 440C stainless steel balls met the criteria in all three environments.
3. The ion-plated silver films met the criteria only in ultrahigh vacuum, failing in humid air and in dry nitrogen where both the film and ball wear rates were on the order of 10^{-5} mm³/N·m.
4. In ultrahigh vacuum the coefficient of friction and endurance (wear) life of the bonded MoS₂ films were superior to those of the magnetron-sputtered MoS₂ and ion-plated silver films.
5. With the bonded MoS₂ and magnetron-sputtered MoS₂ films lower coefficients of friction, film wear rates, and ball wear rates were obtained in dry nitrogen than in ultrahigh vacuum.
6. In humid air, an oxidative environment, the bonded MoS₂ films had higher coefficient of friction (0.14) and shorter wear life (113 570 passes) than the magnetron-sputtered MoS₂ films (0.10 and 277 377 passes, respectively).
7. The ion-plated silver films had a high coefficient of friction (0.43) in humid air but relatively low coefficients of friction in nonoxidative environments (0.20 in ultrahigh vacuum and 0.23 in dry nitrogen).
8. Adhesion and plastic deformation played important roles in sliding friction and wear of the solid lubricating films in contact with 440C stainless steel balls in all three environments. All sliding involved adhesive transfer of materials: transfer of solid lubricant wear debris to the counterpart 440C stainless steel and transfer of 440C stainless steel wear debris to the counterpart solid lubricant.

Reference

1. Jost, H.P.: Tribology—Origin and Future, Wear, vol. 136, 1990, pp. 1–17.

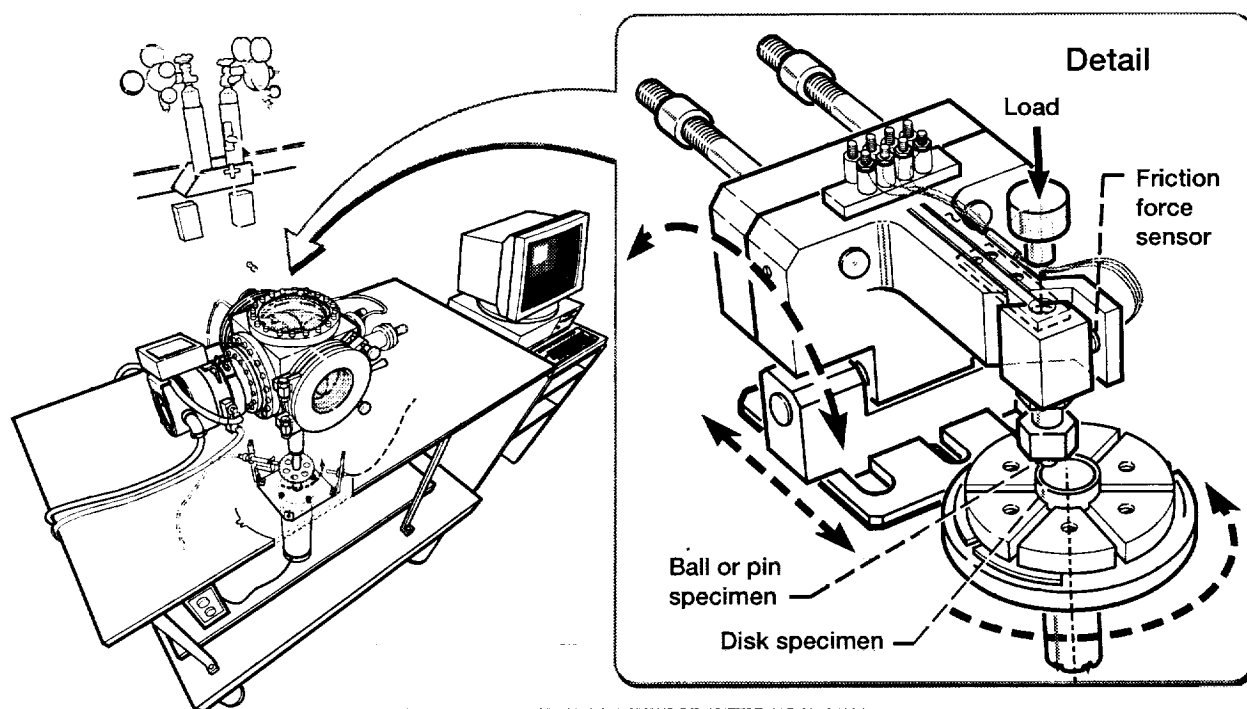
TABLE I.—CHARACTERISTICS OF SELECTED SOLID LUBRICATING FILMS
[Substrate material, 440C stainless steel.]

Film	Film material	Film thickness, μm	Surface roughness of films, R_a , nm	
			Mean	Standard deviation
Bonded MoS ₂	MoS ₂ , polyamide-imide, others (proprietary blend)	10 ± 4	1.2×10^3	2.4×10^2
Magnetron-sputtered MoS ₂	MoS ₂	1.0 ± 0.2	32	4.0
Ion-plated silver	Silver	0.5 ± 0.2	30	3.2

TABLE II.—STEADY-STATE COEFFICIENT OF FRICTION, WEAR RATES, AND WEAR LIFE FOR SELECTED SOLID LUBRICATING FILMS IN SLIDING CONTACT WITH 440C STAINLESS STEEL BALLS

Film	Film material	Steady-state coefficient of friction	Film wear (endurance) life ^a	Film wear rate, mm ³ /N·m	Ball wear rate, mm ³ /N·m
Bonded MoS ₂	Vacuum	0.045	>1 million	6.0×10 ⁻⁸	1.3×10 ⁻⁹
	Air	.14	113 570	2.4×10 ⁻⁶	8.1×10 ⁻⁸
	Nitrogen	.04	>1 million	4.4×10 ⁻⁸	6.9×10 ⁻¹⁰
Magnetron-sputtered MoS ₂	Vacuum	0.070	274 130	9.0×10 ⁻⁸	2.5×10 ⁻⁹
	Air	.10	277 377	2.4×10 ⁻⁷	1.5×10 ⁻⁷
	Nitrogen	.015	>1 million	1.6×10 ⁻⁸	9.9×10 ⁻¹⁰
Ion-plated silver	Vacuum	0.20	364 793	8.8×10 ⁻⁸	2.4×10 ⁻⁸
	Air	.43	8	5.5×10 ⁻⁵	1.2×10 ⁻⁵
	Nitrogen	.23	1040	1.6×10 ⁻⁵	1.6×10 ⁻⁵

^aFilm wear life is determined to be the number of passes at which the coefficient of friction rises to 0.3.



Load, N (g)	5.9 (600)
Mean Hertzian contact pressure, GPa	0.79
Maximum Hertzian contact pressure, GPa	1.19
Ball specimen	6-mm-diameter 440C stainless steel ball
Sliding velocity, m/s	0.2
Environments	Vacuum, 7×10 ⁻⁷ Pa Humid air (relative humidity, ~20%) Dry nitrogen (relative humidity, <1 %)

Figure 1.—Pin-on-disk tribometer in vacuum chamber and conditions of unidirectional, pin-on-disk, sliding friction experiments.

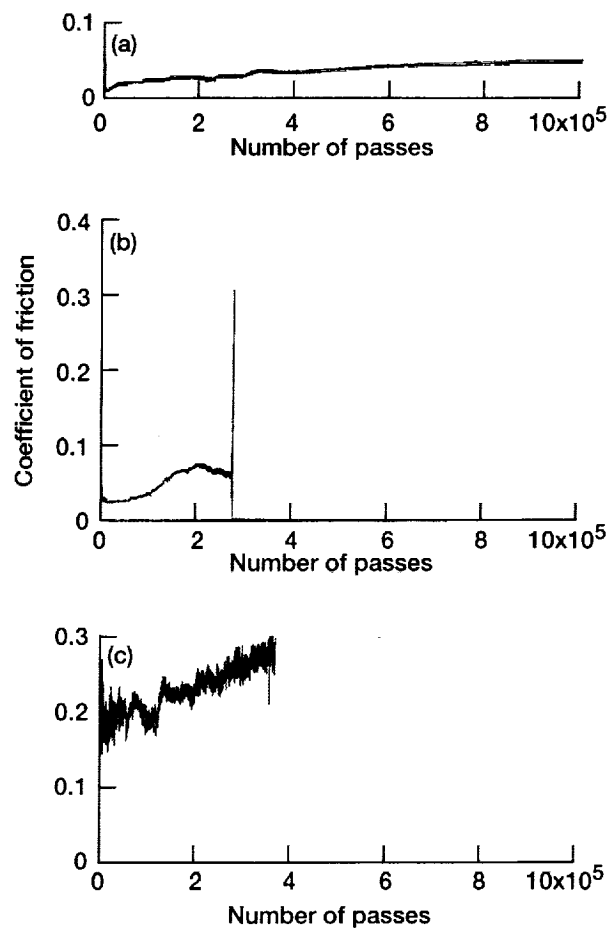


Figure 2.—Friction traces for films of (a) bonded MoS_2 , (b) magnetron-sputtered MoS_2 , and (c) ion-plated silver in sliding contact with 440C stainless steel balls in ultrahigh vacuum.

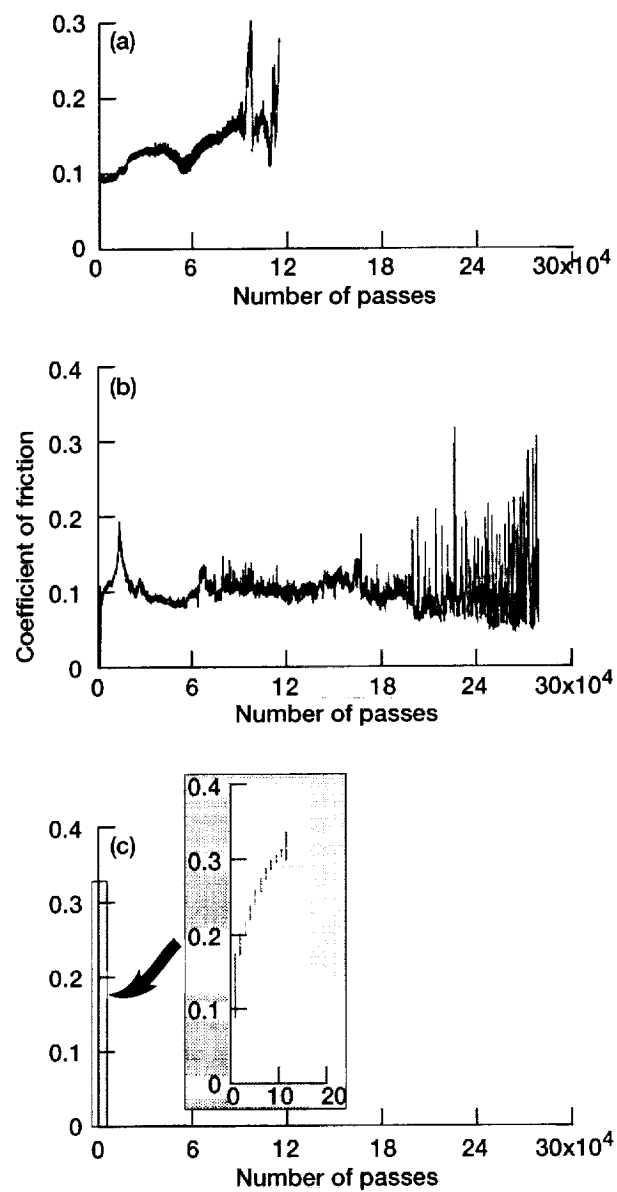


Figure 3.—Friction traces for films of (a) bonded MoS_2 , (b) magnetron-sputtered MoS_2 , and (c) ion-plated silver in sliding contact with 440C stainless steel balls in humid air.

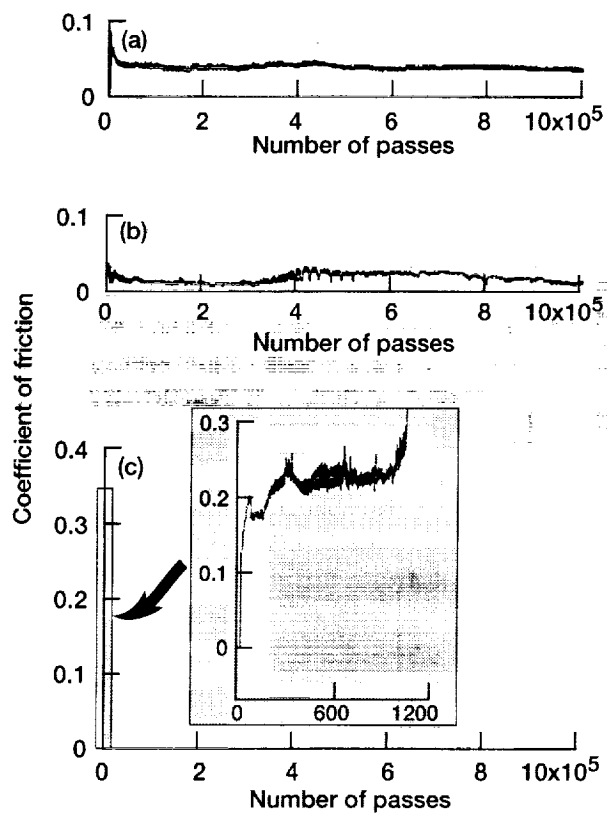


Figure 4.—Friction traces for films of (a) bonded MoS_2 , (b) magnetron-sputtered MoS_2 , and (c) ion-plated silver in sliding contact with 440C stainless steel balls in dry nitrogen.

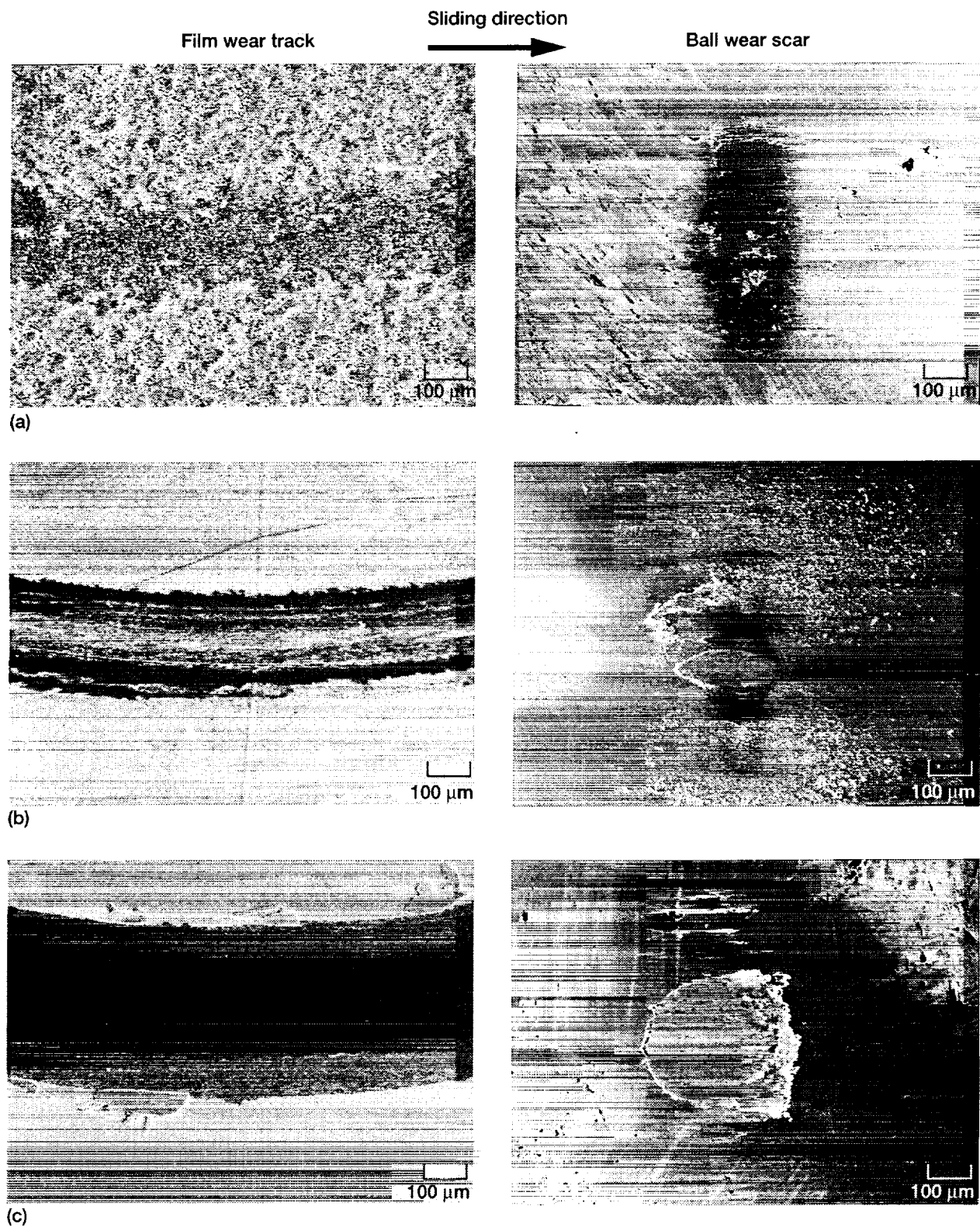


Figure 5.—Wear tracks produced on solid lubricating films and wear scars produced on 440C stainless steel balls in ultrahigh vacuum. (a) Materials pair of bonded MoS₂ film and 440C ball at 1 million passes. (b) Materials pair of magnetron-sputtered MoS₂ film and 440C ball at 274 130 passes. (c) Materials pair of ion-plated silver film and 440C ball at 364 793 passes.

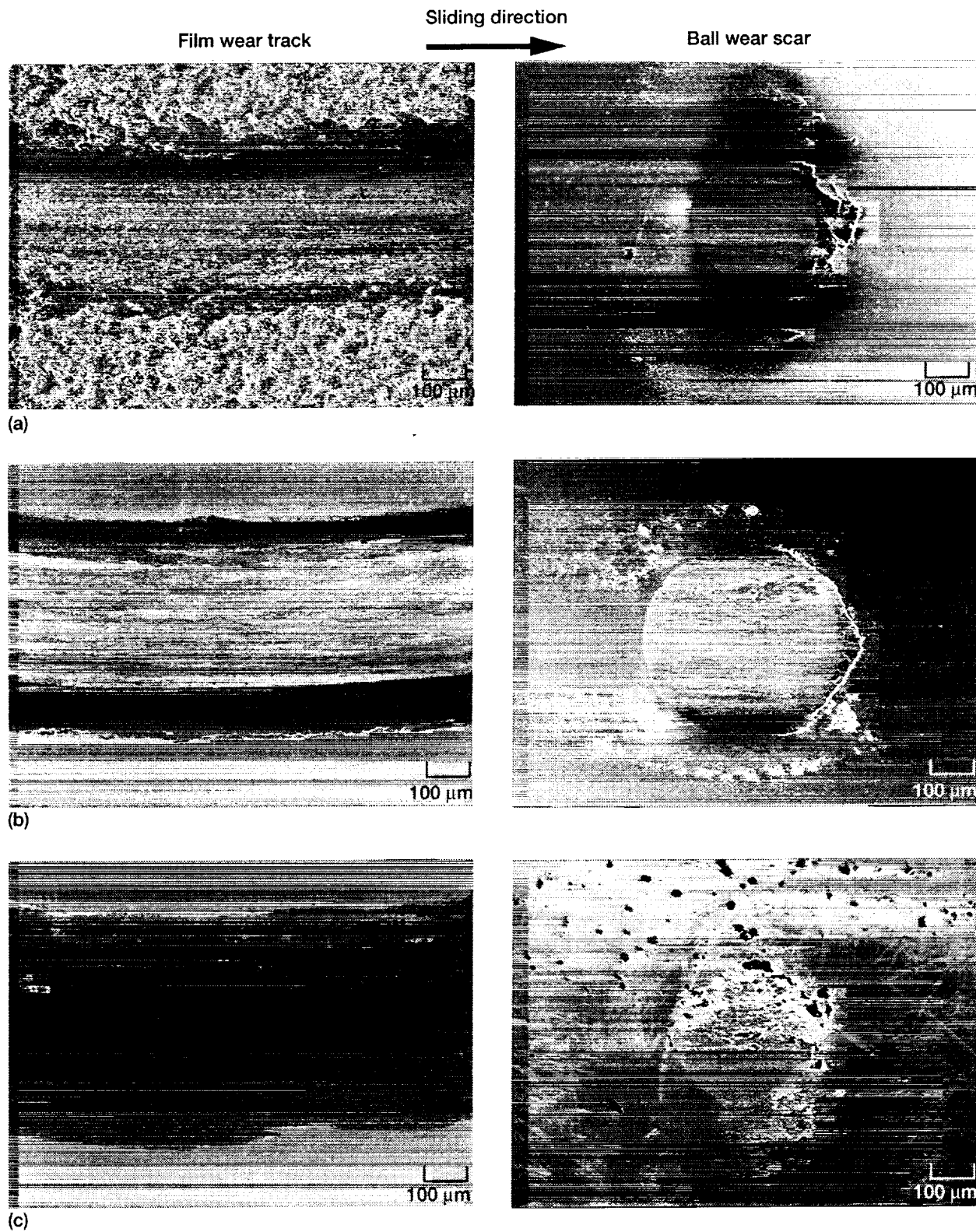


Figure 6.—Wear tracks produced on solid lubricating films and wear scars produced on 440C stainless steel balls in humid air. (a) Materials pair of bonded MoS_2 film and 440C ball at 113 570 passes. (b) Materials pair of magnetron-sputtered MoS_2 film and 440C ball at 277 377 passes. (c) Materials pair of ion-plated silver film and 440C ball at 1000 passes.

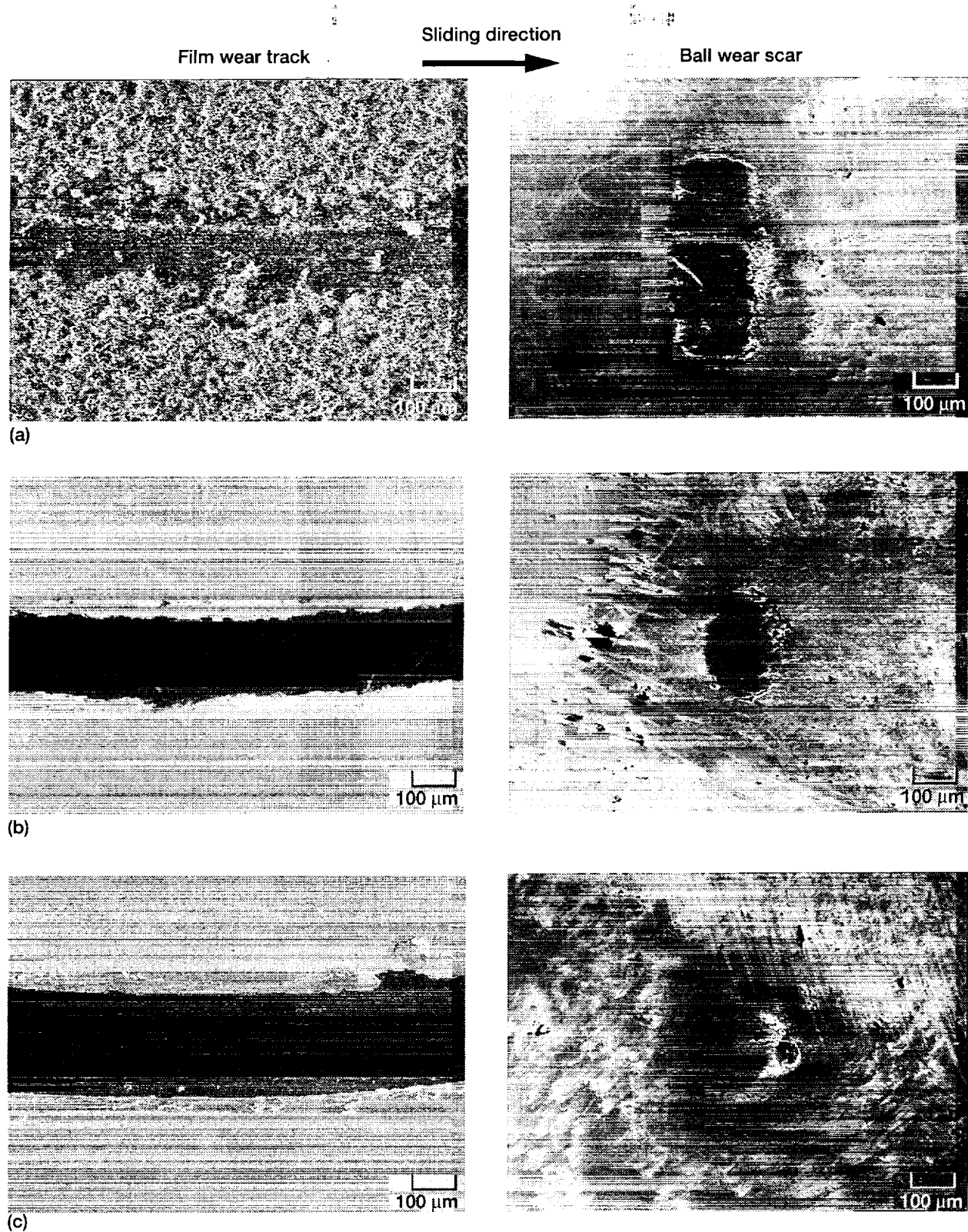


Figure 7.—Wear tracks produced on solid lubricating films and wear scars produced on 440C stainless steel balls in dry nitrogen. (a) Materials pair of bonded MoS₂ film and 440C ball at 1 million passes. (b) Materials pair of magnetron-sputtered MoS₂ film and 440C ball at 1 million passes. (c) Materials pair of ion-plated silver film and 440C ball at 1040 passes.

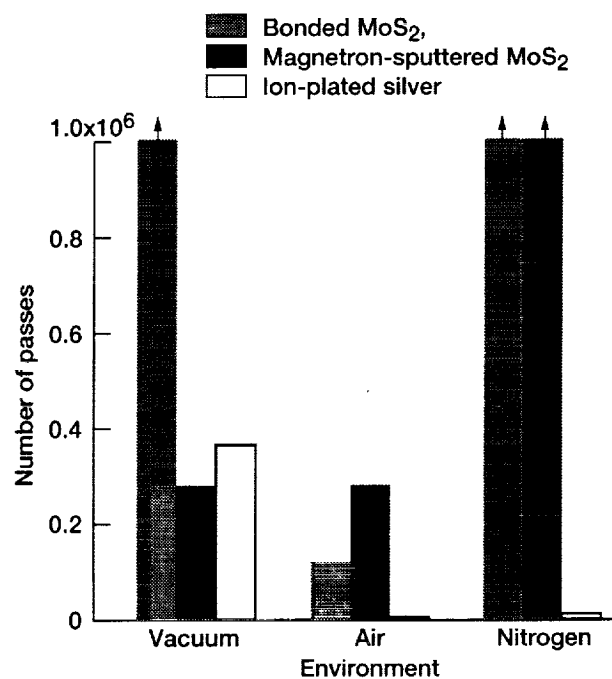


Figure 8.—Sliding wear life of bonded MoS₂, magnetron-sputtered MoS₂, and ion-plated silver films in sliding contact with 440C stainless steel balls in ultrahigh vacuum, in humid air, and in dry nitrogen.

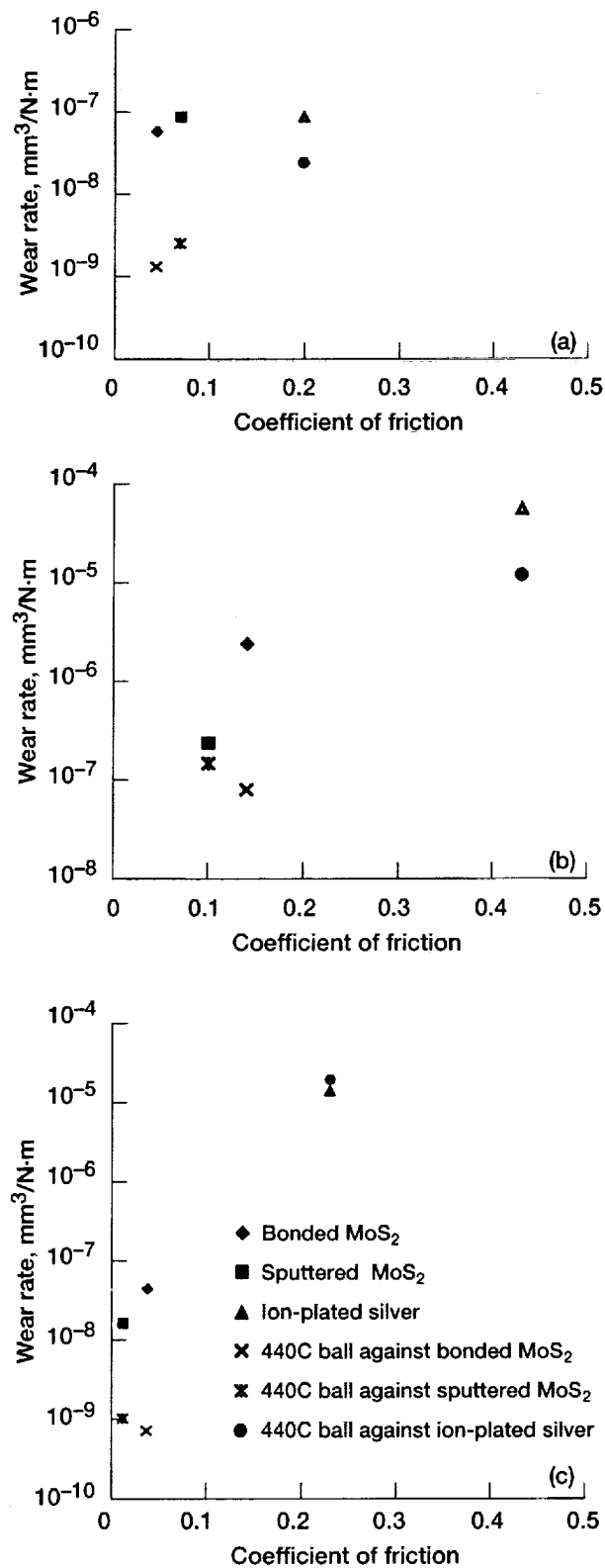


Figure 9.—Steady-state (equilibrium) coefficients of friction and wear rates (dimensional wear coefficients) for solid lubricating films and 440C stainless steel balls (a) in ultrahigh vacuum, (b) in humid air, and (c) in dry nitrogen.

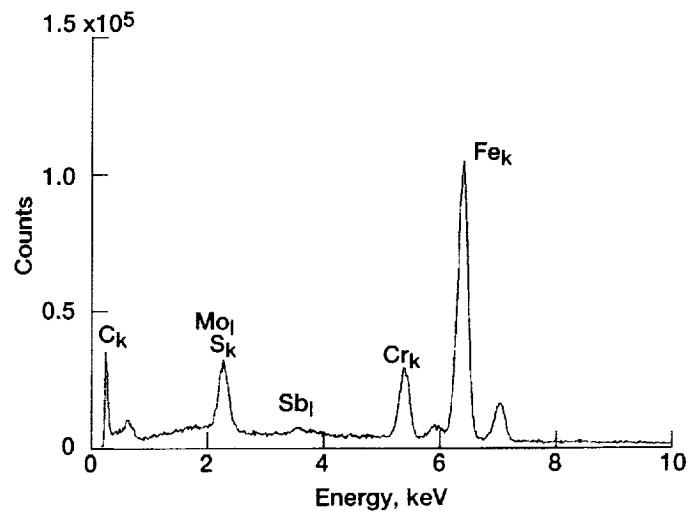
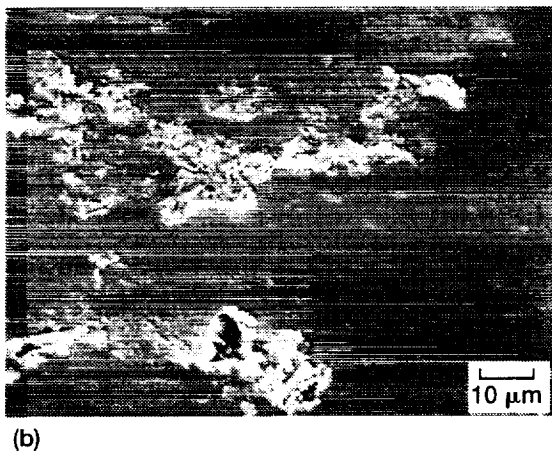
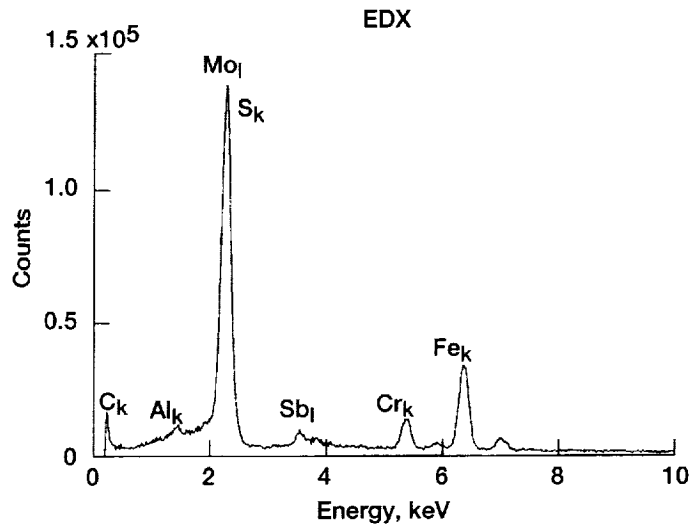
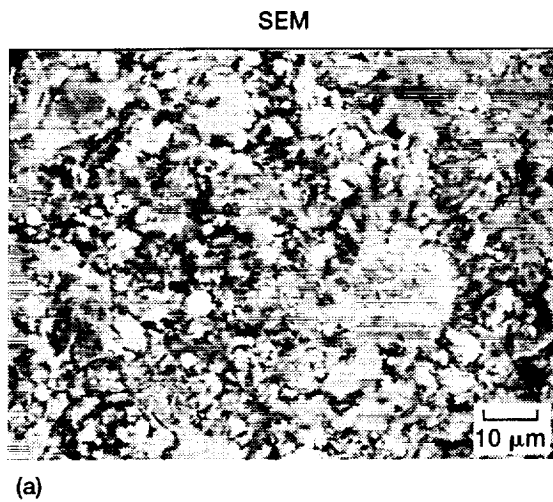


Figure 10.—Morphology and elemental composition (a) of wear track produced on bonded MoS₂ film and (b) of wear scar produced on 440C stainless steel ball in ultrahigh vacuum.

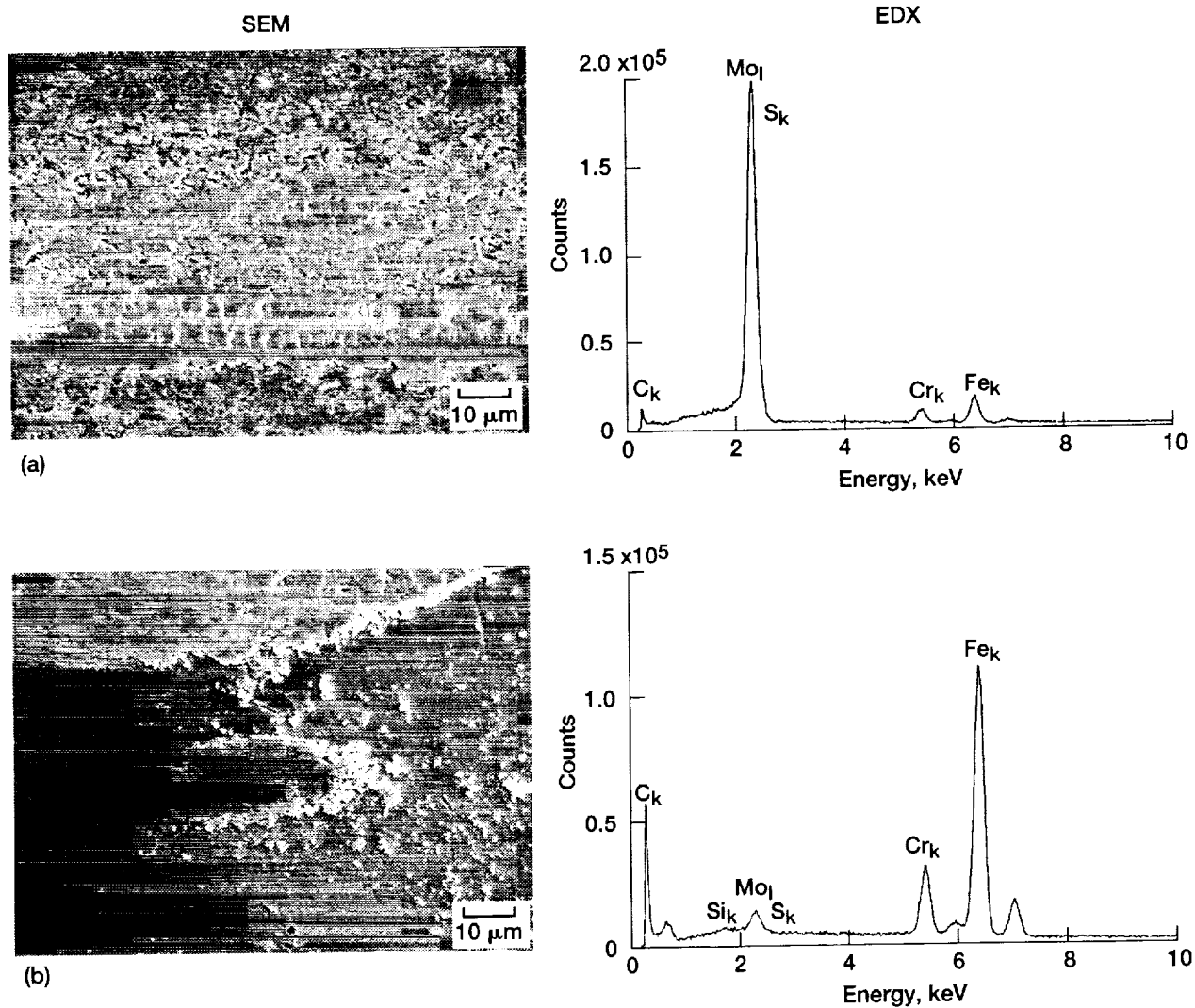


Figure 11.—Morphology and elemental composition (a) of wear track produced on magnetron-sputtered MoS_2 film and (b) of wear scar produced on 440C stainless steel ball in ultrahigh vacuum.

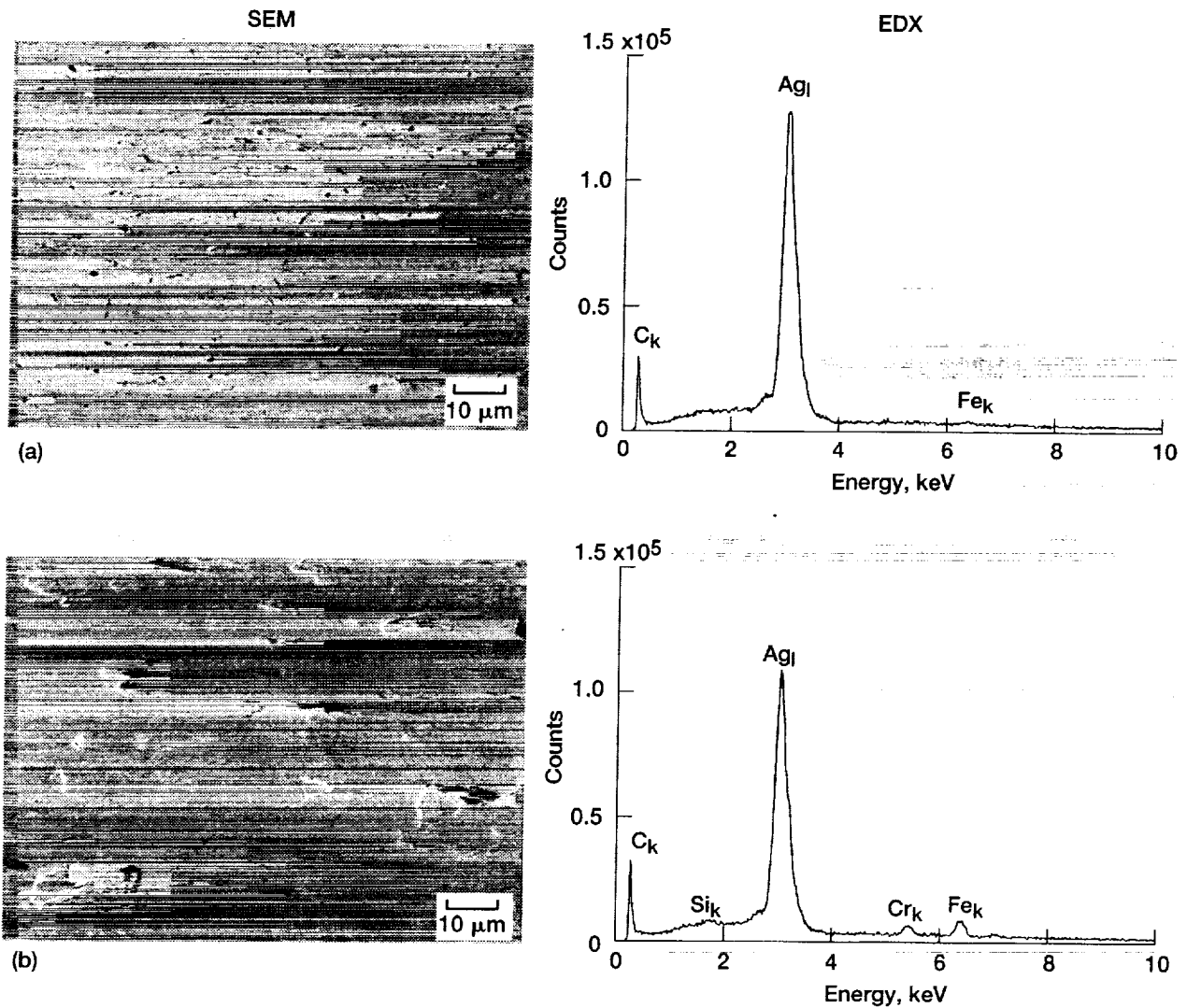


Figure 12.—Morphology and elemental composition (a) of wear track produced on ion-plated silver film and (b) of wear scar produced on 440C stainless steel ball in ultrahigh vacuum.

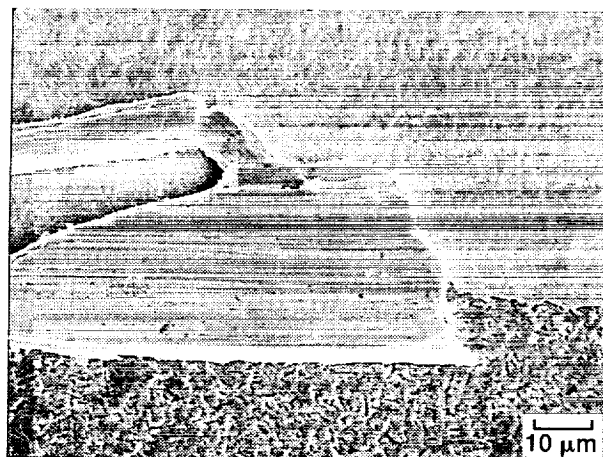


Figure 13.—Plate-like silver wear debris produced on ion-plated silver film in ultrahigh vacuum.

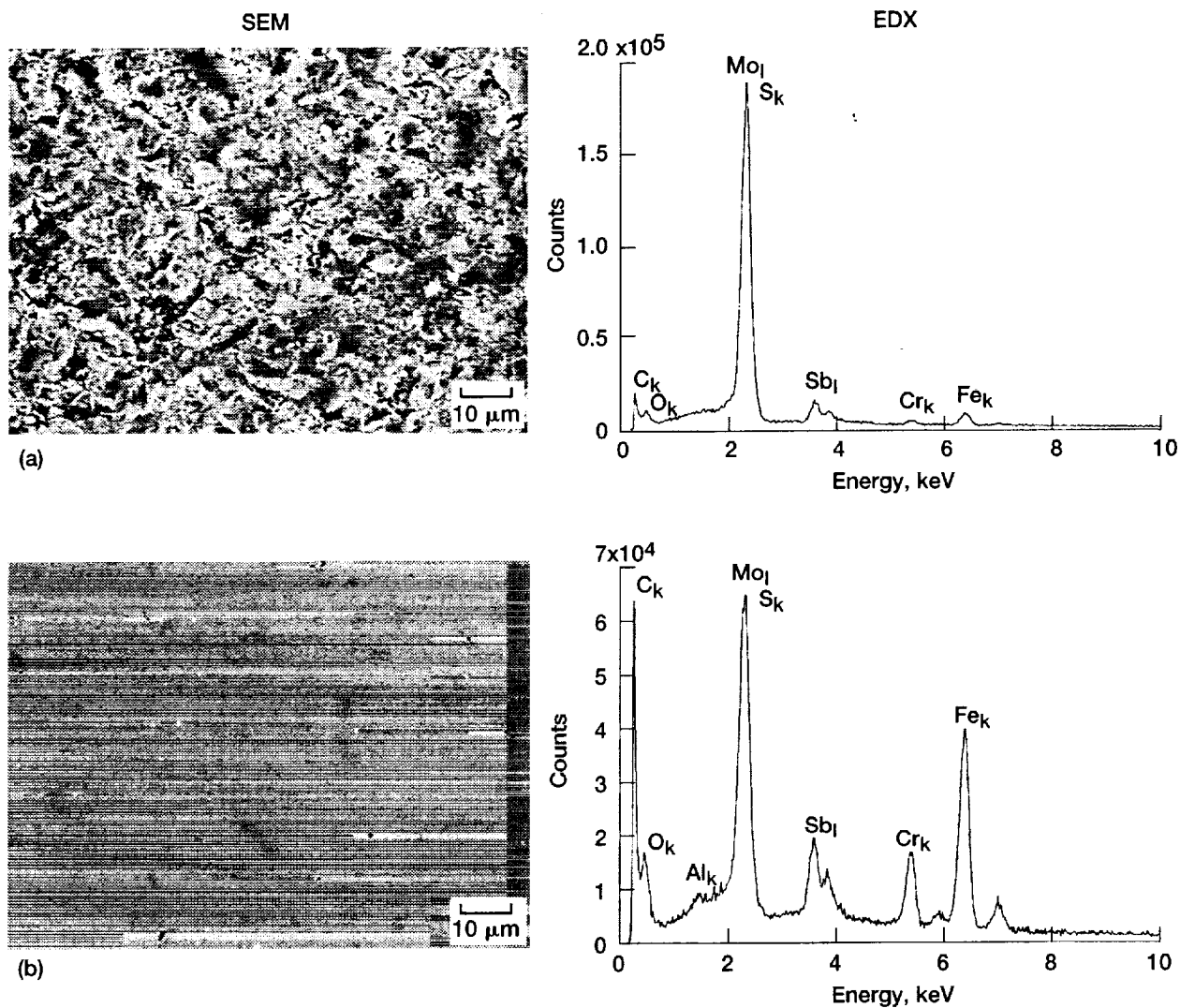


Figure 14.—Morphology and elemental composition (a) of wear track produced on bonded MoS₂ film and (b) of wear scar produced on 440C stainless steel ball in humid air.

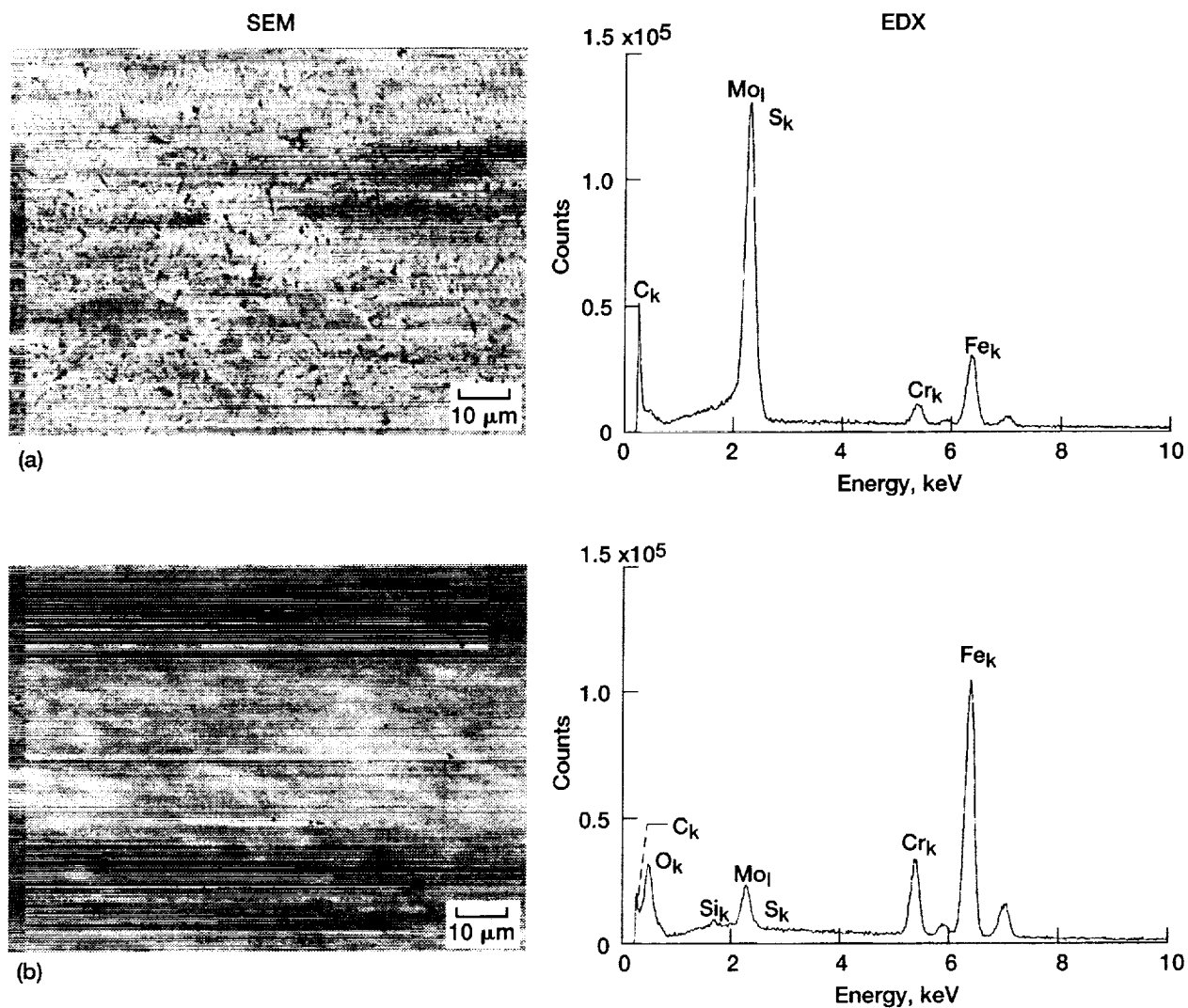


Figure 15.—Morphology and elemental composition (a) of wear track produced on magnetron-sputtered MoS_2 film and (b) of wear scar produced on 440C stainless steel ball in humid air.

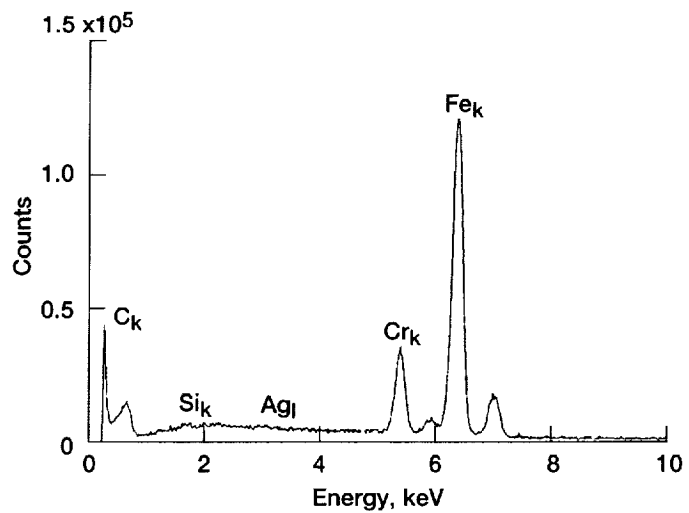
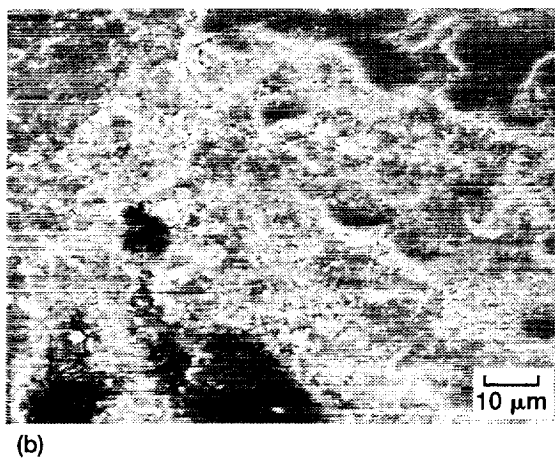
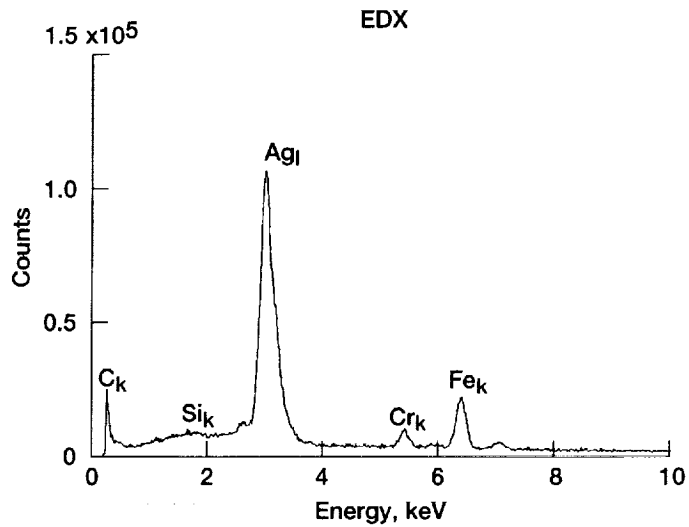
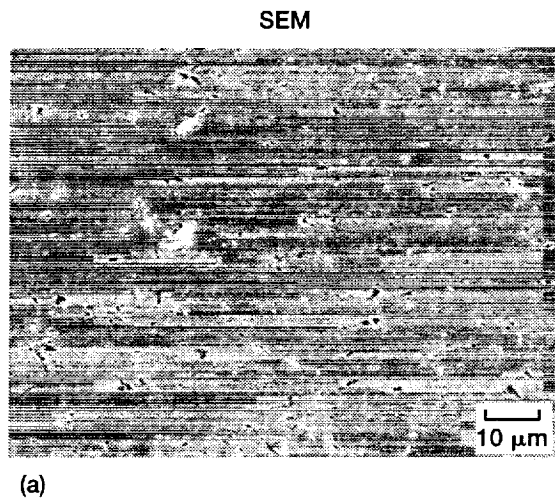


Figure 16.—Morphology and elemental composition (a) of wear track produced on ion-plated silver film and (b) of wear scar produced on 440C stainless steel ball in humid air.

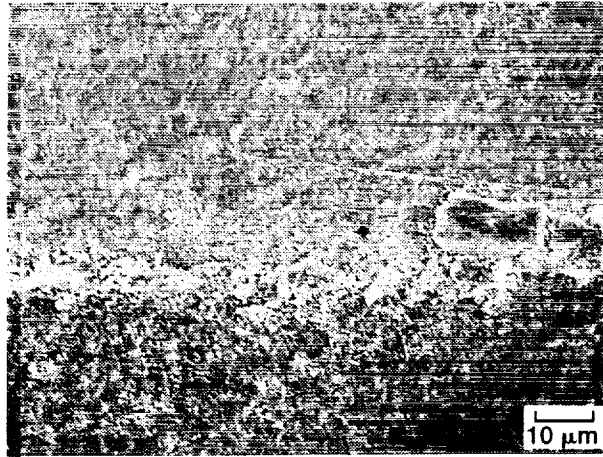


Figure 17.—Plate-like silver wear debris produced on ion-plated silver film in humid air.

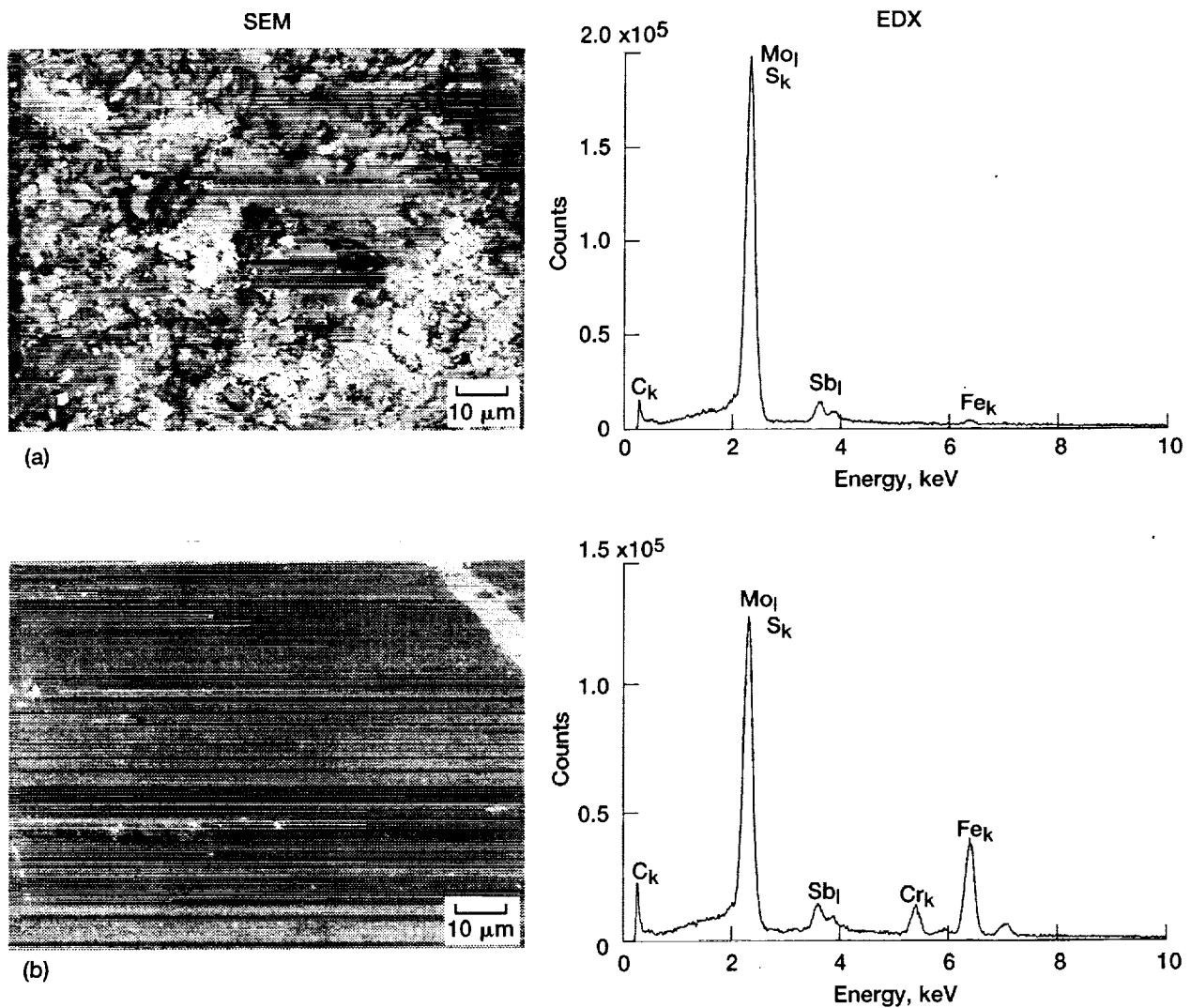


Figure 18.—Morphology and elemental composition (a) of wear track produced on bonded MoS_2 film and (b) of wear scar produced on 440C stainless steel ball in dry nitrogen.

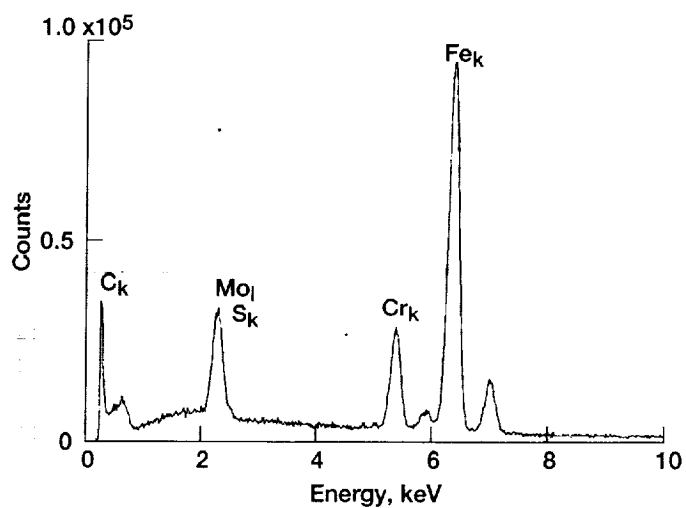
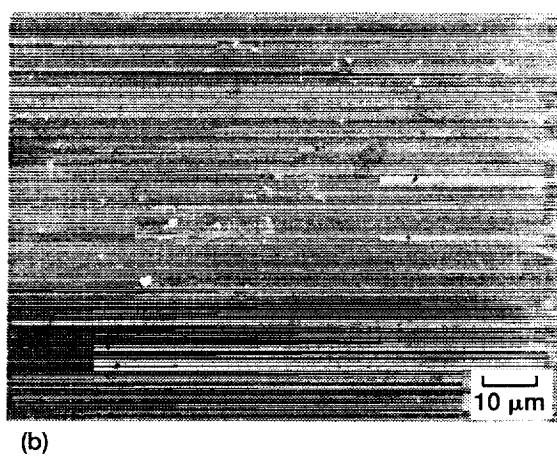
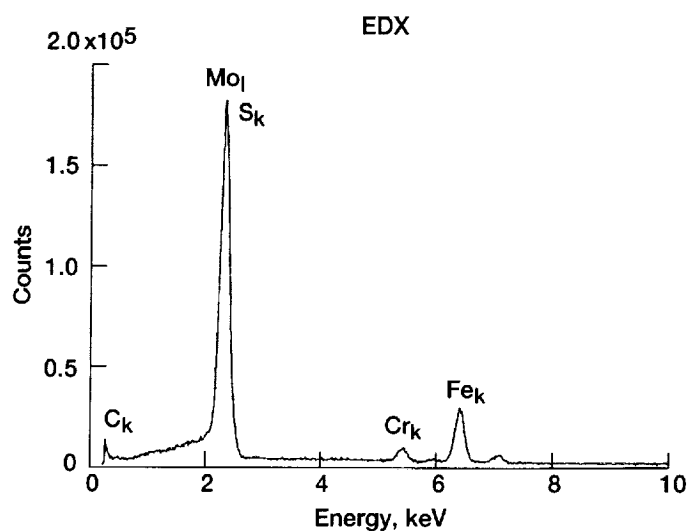
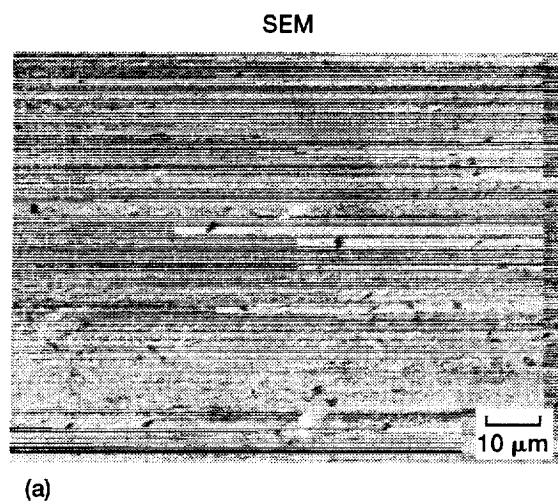


Figure 19.—Morphology and elemental composition (a) of wear track produced on magnetron-sputtered MoS₂ film and (b) of wear scar produced on 440C stainless steel ball in dry nitrogen.

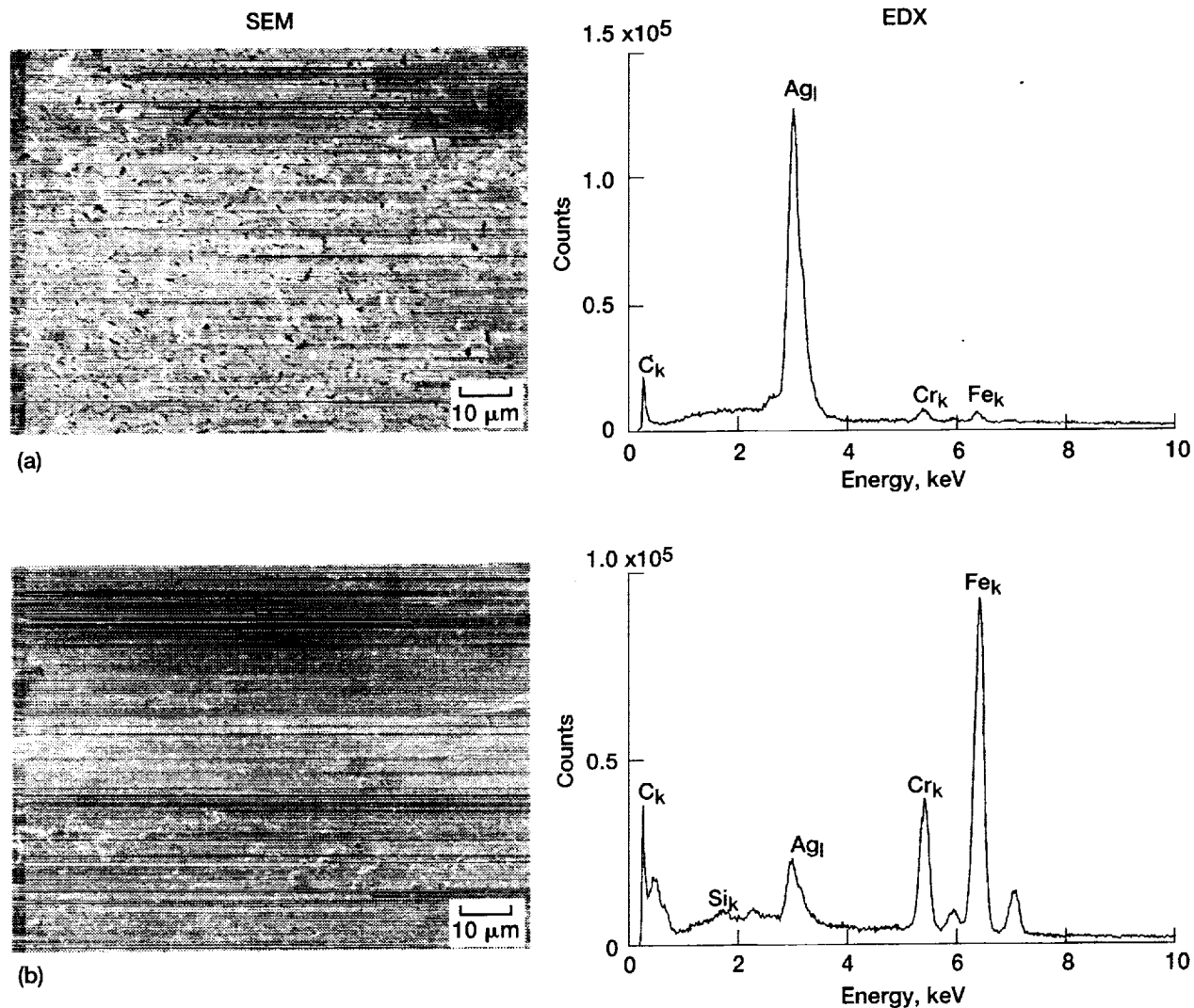


Figure 20.—Morphology and elemental composition (a) of wear track produced on ion-plated silver film and (b) of wear scar produced on 440C stainless steel ball in dry nitrogen.

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13. ABSTRACT (Maximum 200 words) To evaluate commercially developed solid film lubricants for aerospace bearing applications, we investigated the friction and wear behavior of bonded molybdenum disulfide (MoS ₂), magnetron-sputtered MoS ₂ , and ion-plated silver films in sliding contact with 6-mm-diameter AISI 440C stainless steel balls. Unidirectional sliding friction experiments were conducted with a load of 5.9 N (600 g), a mean Hertzian contact pressure of 0.79 GPa (maximum, 1.19 GPa), and a sliding velocity of 0.2 m/s at room temperature in three environments: ultrahigh vacuum (7×10 ⁻⁷ Pa), humid air (~20 percent humidity), and dry nitrogen (<1 percent humidity). The resultant films were characterized by scanning electron microscopy, energy-dispersive x-ray spectroscopy, and surface profilometry. Marked differences in friction and wear resulted from the environmental conditions and the film materials. The main criteria for judging the performance were coefficient of friction and wear rate, which had to be less than 0.3 and on the order of 10 ⁻⁶ mm ³ /N·m or less, respectively. The bonded MoS ₂ and magnetron-sputtered MoS ₂ films met the criteria in all three environments. Also, the wear rates of the counterpart AISI 440C stainless steel balls met that criterion in all three environments. The ion-plated silver films met the criteria only in ultrahigh vacuum. In ultrahigh vacuum the bonded MoS ₂ films were superior. In humid air the bonded MoS ₂ films had higher coefficient of friction and shorter wear life than did the magnetron-sputtered MoS ₂ films. The ion-plated silver films had a high coefficient of friction in humid air but relatively low coefficients of friction in the nonoxidative environments. Adhesion and plastic deformation played important roles in all three environments. All sliding involved adhesive transfer of materials.				
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